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Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia

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ABSTRACT

The main causes of global warming are now attributed to the burning of fossil fuels. Saudi Arabia is the world's largest producer and exporter of total petroleum liquids, and one of the largest consumers of total primary energy. The activities which are mainly responsible for significant greenhouse gas emissions are consistently in the upslope. The electricity generation, the solid waste management, and the agricultural sectors are responsible for the highest share of emissions of CO_2, CH_4, and N_2O, respectively. The results of current research provided the initial justifications for the renewable energy sources such as solar and wind energy conversion, and hybrid systems. The Master Gas Collection System of Saudi Aramco can be considered as a remarkable step forward in lowering CH_4 emissions from the oil and gas fields. The integrated efforts of the public and private sectors are essential for development and implementation of appropriate strategies to reduce greenhouse gas emissions. The study provides an overview of Saudi initiatives related to policy, plan, program, and/or project towards the reduction of greenhouse gases and enhancement of carbon capture and storage.

Contents

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1. Introduction

The terrestrial carbon cycle has undergone direct and indirect changes over the last 200 years. Direct changes are the results of the interaction between an increasing global population and land use, and indirect changes have been the consequences of these changes. Sabine et al. [125] mentioned that the addition of around 400 Pg C to the atmosphere mainly through the burning of fossil fuels and land-use change mainly contributed to the rise in atmospheric CO_2 from 280 to around 380 ppm. The changes in the land-use contribute significantly in altering ecosystem productivity in terms of carbon storage [74,103,143]. It is estimated that the human actions are responsible for the transformation up to 50% of the earth's land surface [147].

The typical approaches taken to address the problem of greenhouse gas emission include the adoption of a plan, policy and program, that in combination reduce the emissions of greenhouse gas (GHG). These approaches emphasize on renewable and green energy sources, rational use of energy (RUE), and more energy efficient technologies. At the same time, in order to address the rising greenhouse gas concentrations in the atmosphere, protecting and increasing the sinks for CO_2, CH_4, and N_2O may play a crucial role along with the cutting of anthropogenic emissions in determining how the climate of the 21st century unfolds [116].

The main causes of global warming are attributed to burning of fossil fuels, such as coal, oil, and natural gas, and releasing into the atmosphere, the emission of carbon dioxide and other greenhouse gases. Saudi Arabia is the world's largest producer and exporter of total petroleum liquids, and its economy remains heavily dependent on oil and petroleum-related industries, including petrochemicals and petroleum refining [46]. Oil export revenues have accounted for around 90% of total Saudi export earnings and state revenues. As well, oil demand is expected to grow in the future due to the continuing increase in world demand and to the lack of commercially viable and easily storable alternative, non-fossil energy sources [69]. Moreover, the world demand for natural gas is also projected to increase rapidly and around 60% of the increase in annual gas demand is accounted for by the power generation sector [43].

In line with the Kingdom's strong commitment to sustainable development, the public and private sector, and even the people of Saudi Arabia started considering climate change issues in the list of priorities. The Kingdom ratified the United Nations Framework Convention on Climate Change (UNFCCC), and has accessed the Kyoto Protocol [144]. The country is showing keen interest to actively participate in the development of Renewable Energy Sources (RES) and RUE. A process of environmental awakening is also being observed in the Kingdom. It is expected that the use and development of RES and RUE can make a significant contribution to improving environmental protection [30,55].

The next section will briefly address the main challenges facing developing countries in combating greenhouse gas emissions. The third section analyzes the contributions of different sectors in the greenhouse gas emissions. The fourth section elaborates the different initiatives taken by the Kingdom in order to control and mitigate the greenhouse gas emissions or improve sinks of greenhouse gases. The fifth section sheds light on the relevant present and future research on mitigation measures. The last section draws appropriate conclusions.

2. Challenges in the developing countries

Typically, GHG emissions are significantly affected by economic and population growth, increased transportation use, and industrialization [111]. Although economic development and greenhouse gas reduction strategies are not conflicting in many cases, the developing countries are now facing the challenge of addressing both the issues collectively without hampering the national economy or environment. However, many developing countries started considering the renewable resources along with fossil fuels, especially the countries that heavily rely on imported fossil fuels. They are also taking initiatives to improve the sinks of greenhouse gases. In the next few paragraphs, the challenges faced by those countries to ensure reduction of greenhouse gases will be briefly elaborated.

The energy sector plays a very important role in CO_2 emissions in Nigeria. In order to reduce the greenhouse gas emissions, a set of viable mitigation measures have already been identified in the energy sector. Akinbami [68] concluded that the implementation of those so called win–win options will face a number of barriers which include lack of legislative framework, lack of awareness, lack of access to appropriate technology, and inappropriate energy pricing policies. Jaber [73] examined the Jordan's energy sector focusing on greenhouse gas emission reduction options and constraints related to the implementation of mitigation measures. The energy sector is mainly dependent on fossil-fuel combustion and concluded that the mitigation measures to reduce CO_2 emissions depend on awareness, access to appropriate technology, legislative framework, and energy pricing policies.

A rapid and accelerated growth in the energy sector is envisaged in India due to the future economic development trajectory. But the dependency on fossil fuels in the electricity generation causes huge negative environmental externalities. It inspires to focus on renewable energy sources. Although India has considerable experiences and capabilities on renewable electricity technologies, a number of techno-economic, market-related, and institutional barriers impede technology development and penetration [56].

Over the next few decades, electricity demand in developing countries is expected to grow at more than 6%, whereas the rate is little over 1% in the developed world [131]. It has serious environmental implications for both the countries themselves and the world at large. Schramm [131] commented that capital needs and environmental impacts can be reduced by more than one half if the operational performance of the power sectors could be brought to the standards prevailing in the developed world. De Araujo [41] investigated the development with respect to the efficiency of industrial energy use in Africa, Asia and Latin America. Industrial energy conservation and improved energy efficiency should be national policy priorities in the developing countries to reduce greenhouse gas emissions. Liaquat et al. [92] critically investigated the potentials and limitations of biofuel production and utilization in developing countries to reduce greenhouse gas emissions and fossil fuels' dependency. But it requires careful investigation before promoting biofuels because it may cause conflict with food production [36]. Couth and Trois [109] investigated the waste management practices across Africa and found out that the degradation of municipal solid waste is a major contributor to greenhouse gas emissions and the average organic content of urban municipal solid waste is around 56%.

Saudi Arabia is facing a unique problem of greenhouse gas emissions because its economy is oil-based and the whole energy sector is dependent on fossil fuels. The high oil prices during 2004–2008 gave the Kingdom ample opportunities to increase development activities. The vibrant economy affects the domestic energy consumption significantly. The cheap availability of fossil fuels in the domestic market discourages investment on renewable energy sources and the use of public transportation. Like other developing countries, the public awareness, access to appropriate technology, legislative framework, and energy pricing policies are not matured enough to account for significant reduction of greenhouse gas emissions.

3. Analysis of greenhouse gas emissions

Presidency of Meteorology and Environment (PME) submitted the first national communication of Saudi Arabia to UNFCCC in which the national greenhouse gas inventory for the year 1990 is also reported [110]. In that inventory, CO_2 emissions were estimated at 140,958 Gg (1 Giga gram = 1000 tons), and the energy sector contributed 90% of the total CO_2 emissions, followed by the industrial processes and product use sector (8%). The main source categories including electricity generation, road transport, fuel combustion in desalination plants, and petroleum refining contributed 26%, 25%, 15% and 10% of the total CO_2 emissions, respectively. The emissions of CH_4 were 787 Gg in which the waste sector contributed 77% of the total emissions followed by the agriculture (11%), and the energy sector (11%). The solid waste management was the main source category which contributed to the 76% of total CH_4 emissions, followed by the enteric fermentation (9%) which is a digestive process of breaking carbohydrates into simple molecules by microorganisms. The agriculture sector was the major contributor with 91%, followed by the waste (6%) to the total emissions of 33.8 Gg N_2O. The N_2O emissions from the source categories of agricultural soils and manure management were 69% and 21%, respectively. This information indicated that the energy sector carries the highest potential for the mitigation of greenhouse gas emissions in terms of CO_2 equivalent.

The analysis of energy consumption data revealed that the consumption of petroleum products (mainly include motor gasoline, jet fuel, kerosene, distillate fuel oil, residual fuel oil and liquefied petroleum gases) and natural gas, and electricity, typically follows an increasing trend (Fig. 1). The per capita electricity consumption is also increasing consistently (Fig. 2). The exhaust from vehicles, which play a major role in CO_2 emissions, is also showing consistent increase in every year (Fig. 3). According to USEPA [145], CH_4 emissions from municipal solid waste by Saudi Arabia were 12.4, 15.5, and 16.8 million tons of CO_2 equivalent ($MtCO_2eq$) in 1990, 1995, and 2000, respectively.

The analysis of national development plans shed light on the domestic consumption of petroleum products and the rate of changes over the years. It is reported that the local fossil fuel energy consumption increased at an average annual rate of 10.4% from 1.11 million barrels in 1970 to 1.02 billion barrels in 2008 [101]. The current average annual increase of the domestic consumption of refined oil products (excluding consumption by oil industry) varies approximately between 11% and 13%. The consumption of all types of petroleum products is increasing in the Kingdom (Fig. 4). Generally, the main parts of gasoline and jet fuel are used in the transportation sector including road transportation and aviation. Diesel fuel is consumed for electricity generation, petroleum refining, cement industry, heavy vehicles, navigation, and railway transportation. Liquefied petroleum gases (LPG) are consumed in petroleum refining, residential and commercial activities. Fuel oil is consumed in electricity generation, petroleum refining, and navigation. Therefore, the increase of the consumption of any specific type of fuel indicates the increase of the corresponding activities. However, it may also be affected by the policy changes such as fuel switching for certain activities.

The rise in GHG emissions in the Kingdom can be attributed to rapid development and industrialization, and the electricity generation for continually increasing development of domestic, tertiary and industrial establishments [111].

4. Saudi initiatives

Saudi Arabia is the largest consumer of petroleum in the Middle East and the consumption growth has been encouraged by the economic boom due to historically high oil prices and large fuel subsidies. In 2006, Saudi Arabia was the 15th largest consumer of total primary energy, of which 60% was petroleum-based and the remaining 40% was made up of natural gas [44]. These circumstances force the Kingdom to take positive initiatives to curb greenhouse gas emissions. The research community is showing interest to actively participate in the development of RES and RUE. A process of environmental awakening is also being observed in the Kingdom. The use and development of RES and RUE can make a significant contribution to improving environmental protection [30,55]. The Kingdom adopted a holistic approach by exerting its sincere effort in almost all the sectors which affect the environment, to ensure a sustainable environment for the present and future generations.

Since the late 1970s, several universities and research institutions in the Kingdom have attempted to investigate renewable technologies and applications [34]. The research work covered both theoretical and experimental investigations on components and systems but only in a few areas such as the operation of Photovoltaic (PV) systems [34] and wind energy resources [48]. The solar and wind energy resources and biomass potential of Saudi Arabia are estimated to 6–8 kWh/m^2/day, 4.5–6.5 m/s, and 3.0 million ton of oil equivalent (mtoe)/year, respectively [16,53,64].

Currently, the world-wide efforts on the exploitation of renewable energy sources increased significantly to ensure environment-friendly sustainable development and to mitigate future energy challenges [49]. In the context of Saudi Arabia, the local consumption of renewable energy can benefit the Kingdom by freeing up larger quantities of petroleum products for exports and reducing air pollutant and greenhouse gas emissions [18]. Moreover, renewable energy sources can meet a significant share of energy requirement of the Kingdom. Theoretically, it is argued that the Kingdom can meet the population's energy needs with the amount of renewable energy input adequately [18].

4.1. Rational use of energy initiatives

The Ministry of Water and Electricity (MOWE) has initiated several steps to implement energy conservation and to reduce peak load demand which include the establishment of an Energy Conservation and Awareness Department, imposing limits to the maximum power that can be delivered to electricity consumers, establishing demand-side management actions, and rationalizing the use of electricity [5]. It is estimated that 871 MW peak load reductions were achieved by the various sectors during 2001. Moreover, the MOWE in collaboration with Saudi Electric Company (SEC) has begun to implement procedures enabling the commercial, governmental, agricultural, and industrial sectors to reduce and shift peak loads; stopped irrigation during peak load times in the agricultural sector; published and distributed the first edition of the Energy Conservation and Load Management Consumers' Guide; organized workshops and meetings to promote public awareness of energy conservation; and organized site visits to major consumers in the governmental sector to stress the importance of energy conservation procedures and to introduce load reduction tools [5].

As an endeavor to ensure RUE Source Energy, a major Saudi energy company is building an efficient power plant that will provide the King Road Tower with electricity and air conditioning services [25]. This project will use absorption chillers to produce refrigeration by capturing the waste heat generated by the diesel power plant. It will reduce CO_2 emissions by about 10,000 tons/year.

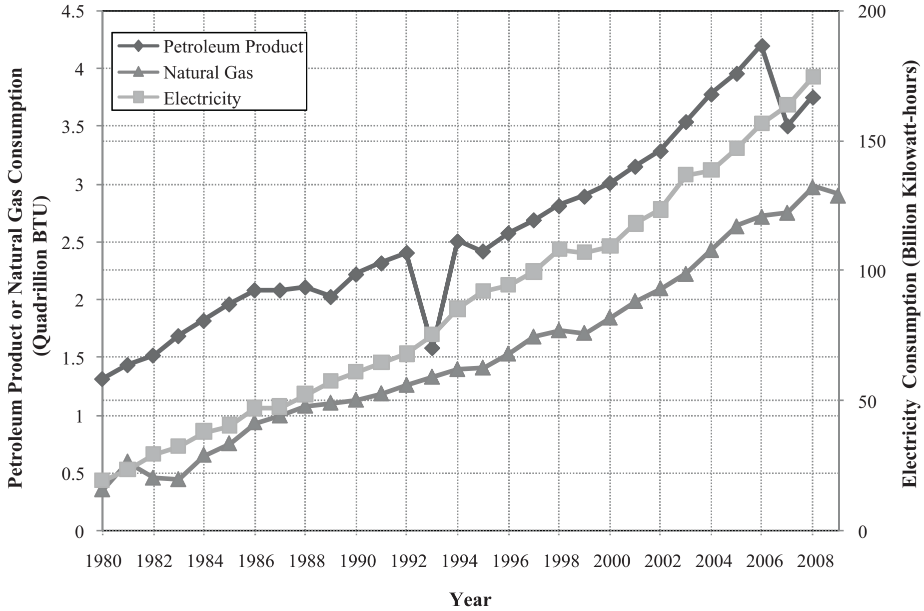

Fig. 1. The annual consumption of electricity and petroleum and natural gas in Saudi Arabia.

Source: [46].

4.2. Wind energy conversion initiatives

The development in the field of manufacturing and application of wind energy industry is increasing the merits of wind energy exploitation [48]. King Abdul Aziz City for Science & Technology (KACST) prepared the wind atlas for the Kingdom which shows that the mean annual wind speeds in certain regions of the Kingdom are more than 4 m/s at 10 m height [76]. It can be expected that the speeds would be higher at the typical heights of modern wind turbines which are typically mounted on towers of 100 m or even higher. KACST installed both small and large wind energy conversion systems at Yenbo and Al-Wajh on the Red Sea coast, Dhahran on the Arabia Gulf coast and Quaisumah in the north east of the Kingdom as a part of a feasibility study of wind energy utilization [21]. Saudi ARAMCO installed two wind turbines each of 6 kW at two different remote locations to generate power for the communication towers. King Fahd University of Petroleum & Minerals (KFUPM) conducted wind power resource assessment for twenty locations at national and international airports in the Kingdom [118].

4.3. Solar energy conversion initiatives

The presence of direct solar radiation ranging from 30 MJ/m^2/day in some regions in the summer to 24 MJ/m^2/day anywhere in the country, even in the month of January, makes the Kingdom very attractive for solar thermal technology [18]. Depending on the capability of current solar photovoltaic technologies, Alnatheer [18] hypothetically argued that less than approximately 0.2% of the combined land area of the Kingdom has to be covered with solar photovoltaic cells to meet all of its energy needs. Saudi Arabia has huge potential for exploiting solar energy due to its geographical location, widespread unused desert land, and year-round clear skies [65]. It is located in the

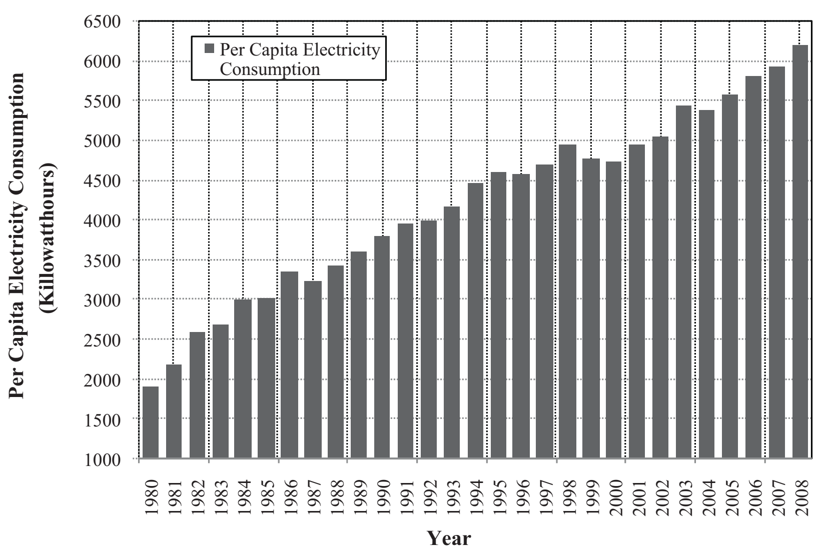

Fig. 2. The average per capita electricity consumption of Saudi Arabia in Kilowatt-hours for different years.

Source: [46].

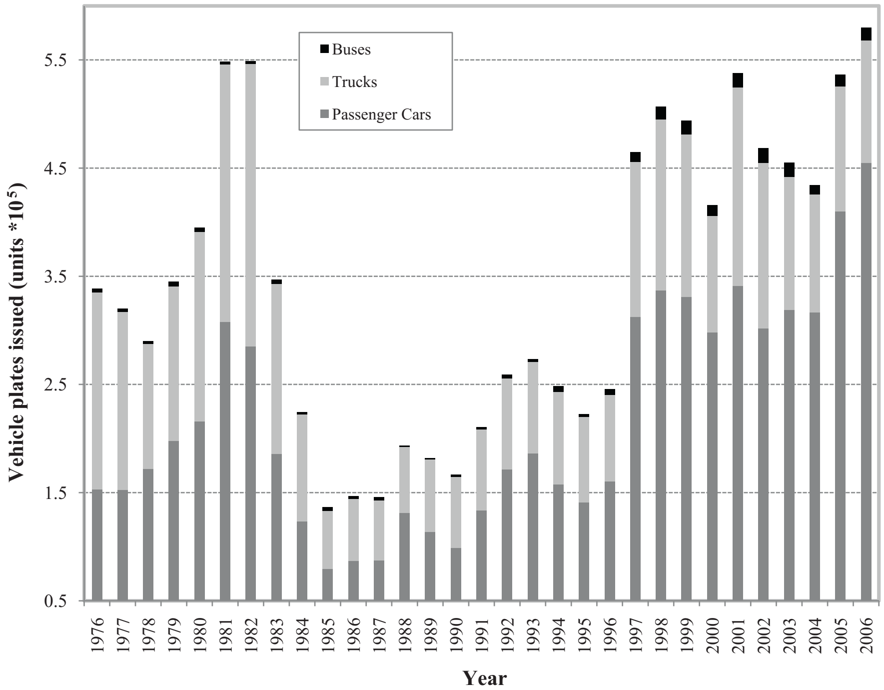

Fig. 3. The total number of vehicle plates issued in each year for different types of vehicles in the Kingdom.
Source: statistical year books of the Kingdom of Saudi Arabia.

heart of one of the world's most productive solar regions receiving the most potent kind of sunlight [39]. The next few paragraphs will shed light on the different key research initiatives taken in the area of solar energy resources.

In order to meet the need of the exact measurements of solar radiation, the Saudi Atlas Project was initiated in 1994, as a joint R&D project between the Energy Research Institute (ERI) and the National Renewable Energy Laboratory (NREL). Twelve locations are connected to a central unit for data collection and the analyzed data are made available on an Internet site. The Solar Village Project aimed to use solar energy to provide power to remote villages and it was designed during the late seventies and started operation in the early eighties. The entire PV project site occupies an area of approximately 67,180 m^2 and the 350 kW concentrator PV electricity-generating power station includes 160 PV arrays, with a total (direct current) peak output of 350 kW, with 1100 kWh

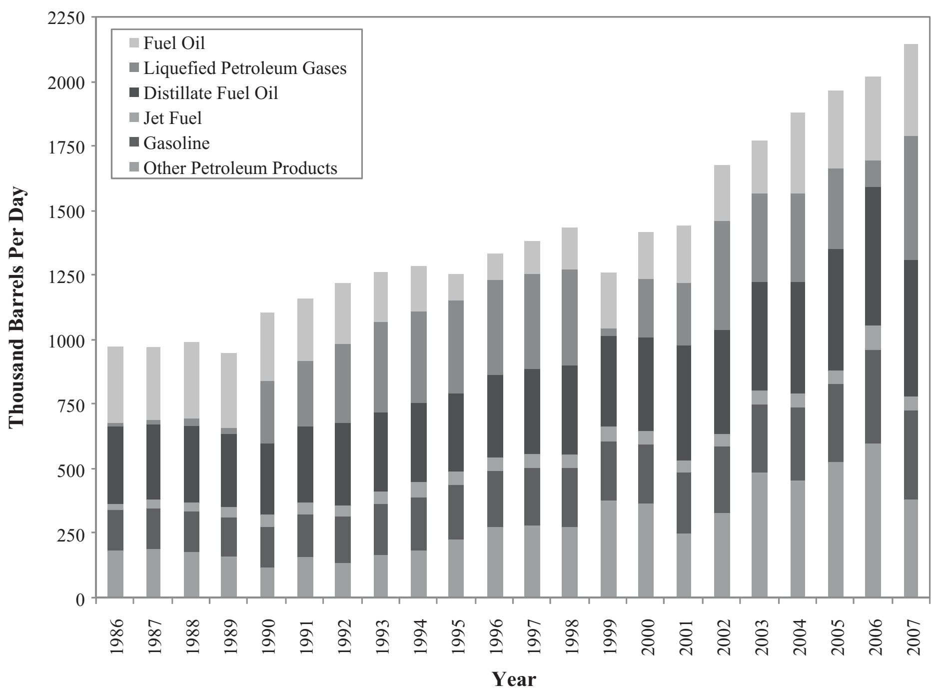

Fig. 4. Different types of fuels consumed domestically in Saudi Arabia.

Source: [46].

lead-acid battery storage, 300 kVA inverter, and a solar-powered weather-data monitoring station [66]. PV technology is a proven technology to use solar energy for generating electricity and is being used for wide range of applications including power supply to remote areas, cathodic protection in pipelines, remotely located oil fields and gas oil separation plants etc. [119]. As a part of the Hysolar Project, a 350 kW solar hydrogen production demonstration plant was started up on 19 August 1993 which has been designed, installed and operated in the Kingdom of Saudi Arabia at KACST research site (solar village) about 50 km North West of Riyadh [66].

Solar radiation based distillation process can be used for water purification. Under the Solar Controlled Environment Agriculture Project (SOLERAS), a solar-powered seawater desalination pilot plant was completed in 1984 at the coastal city of Yanbu, which uses an indirect-contact heat-transfer freeze process to produce 200 m^3 of potable water each day [141]. The SOLERAS program was motivated to develop an industrial solar sea water desalination system for industrial, urban and rural application [82]. The main reason of the Kingdom to participate in projects that SOLERAS researched and developed is to reduce the cost and improve the efficiency of air cooling system [129]. A PV-powered water pumping and desalination plant was installed in 1994 at Sadus Village near Riyadh, which consists of two separate PV fields: one (980 Watt-peak, Wp) is used to energize a 0.55 kW submersible pump for pumping water from a well; the other (10.08 kWp) is used to provide power to a reverse osmosis unit (ROU), with a capacity of 24 m^3/day, and to other accessories and equipment [8].

The Solar Electric Stirling Engine Concentrator (the Solar Thermal Dish Project) is a joint program between KACST and the Federal Ministry of Research and Technology, BMFT, Bonn (Germany), which commenced in 1982 and aimed to produce 50 kW of electrical power from each thermal dish [8]. KACST utilized the PV system to power highway devices in remote locations. One of the projects provided the lighting systems for two remote tunnels located at the southern mountains of Saudi Arabia. The systems generated approximately 1.5 MWh of solar-derived electrical energy each day [10]. A 3-kW PV power system has been established for the duration of 1987–1990 at the Solar Village in order to evaluate the climate effects with the efficiency and output of PV systems [137]. A 6-kW PV system was also installed in Solar Village in 1996 in order to evaluate a scheme for such a system to be integrated with an electric grid, especially during peak hours, for electric load-leveling purposes [138]. In a project on school lighting in rural areas, PV lighting systems were used for 20 schools (of the Ministry of Education) scattered throughout rural areas of the Kingdom. ERI also conducted a few studies for the effective utilization of solar energy in mosques and for the protection of wildlife in Saudi Arabia [63]. ERI also contributed in the development of solar cooling laboratories in universities between 1981 and 1987 due to the importance of solar cooling in the Kingdom [9].

Solar water heating systems (SWHS) can be considered as one of the ways to reduce electricity consumption in water-heating sectors for different hot water applications. ERI is conducting a study on the development of SWHS which will be designed, fabricated and tested for all year seasons [8].

Recently, KACST and International Business Machines (IBM) have developed a research center to determine how best to harness and repurpose the solar energy. It is also intended to build a solar desalination plant to serve 100,000 people in Al Khafji. IBM-KACST jointly developed a nanomembrane that filters out salts and toxin. It is expected that the use of solar power combined with the new nanomembrane will significantly reduce the cost of desalinating sea-water [23]. Conergy, the consortium of Hamburg-based solar experts and Saudi Arabia's National Solar Systems (NSS), has built the 2 MW solar park on the roof top of the King Abdullah University of Science and Technology (KAUST). The power system includes premium components, combining over 9300 high-efficiency solar modules, occupy 11,577 square meters of roof space and produces 3332 megawatt hours (MWh) of clean energy annually. The Solar and Alternative Energy Engineering Research Center at KAUST aimed to provide the foundation for innovation in efficient and low-cost disruptive PV foundational technologies [78].

The country already possesses two factories producing flat plate collectors, which also reflect the progress toward the use of solar energy [43]. First Energy Bank intends to build a polysilicon plant in Saudi Arabia to meet the growing demand for solar energy. The project will be fully operational in 2013. It is also associated with an American company Vinmar International that provided the production target of 7500 tones of polysilicon.

4.4. Other renewable energy conversion initiatives

The Ministry of Higher Education has established Center of Research Excellence in Renewable Energy in the year 2007, at King Fahd University of Petroleum & Minerals (KFUPM). The aim of the Center is to further the scientific/technological development in all major areas of renewable energy. The Center also emphasizes in increasing public awareness and eventually caters to the renewable energy industry in the Kingdom. A Center for Clean Water and Clean Energy at Massachusetts Institute of Technology (MIT) and KFUPM is established recently to conduct research on the technologies related to the production of fresh water and low-carbon energy. King Saud University (KSU) is going to establish a Sustainable Energy Technology (SET) program, which is a multi-disciplinary program, involving the colleges of Engineering (electrical, chemical and mechanical) and science (physics and chemistry). Initially, the program will focus on solar, wind, hydrogen and nuclear energy. The newly established Solar and Photovoltaics Engineering Research Center at KAUST will actively contribute to student education, alternative energy awareness for decision makers and community, active engagement with industry and technology development. KACST initiated a program which promotes collaborative research with industry by establishing Technology Innovation Centers (TICs) at universities. A research initiative of KFUPM concerning carbon capturing and carbon management is already approved by KACST.

The use of geothermal energy system is now recognized as a cost effective standard for energy conservation. Sharqawy et al. [135] conducted a study which deals with the experimental determination of the thermal properties of the underground soil for use in the design of borehole heat exchangers (BHE) which has been installed for the first time in Saudi Arabia.

HYSOLAR is a long-term German–Saudi Arabian cooperative program for research, development and demonstration of solar hydrogen production and utilization of hydrogen as an energy carrier [140]. The aims of the HYSOLAR program include the development of hydrogen utilization for domestic, agriculture and industrial applications [8]. At the end of 1970s there were over 150 solar research projects in academic and research institutes all over the Kingdom [14]. In 1991, the R&D activities on Phosphoric Acid Fuel Cells (PAFC) were initiated at the ERI, under the framework of the HYSOLAR program. In one of the projects of ERI, locally available internal combustion engines, and ceramic mantle gas lamps, have been modified to use hydrogen as a fuel for small-scale demonstration purposes [8]. In ERI, a commercial thermoelectric power generator, supposed to be fuelled by methane or propane, has been modified to operate using hydrogen. After successfully acquiring 'in-house' know-how for developing half-cells, mono-cells, and 100- and 250-W stacks a 1 kW PAFC stack was demonstrated at the ERI. Valuable experience led to an improved design and fabrication of the 1 kW PAFC stack. These lessons will

help to scale-up the power-generating modules (to 10–50 kW) for power utility applications in remote areas [57].

The researchers at KFUPM are actively participating in fuel cell research since 1980s. The efforts are directed to develop Polymer Electrolyte Membrane (PEM) fuel cell system emphasizing three different aspects such as developing novel low cost proton conducting membranes, developing multifunctional catalyst system and development of hydrocarbon based fuel processing systems. Zaidi et al. [153] also explained the ongoing research activities at KFUPM for the development of fuel cell systems. The researchers of Saudi Aramco investigated different candidate fuels for hydrogen generation using autothermal-partial oxidation reforming and water-shift reaction technologies [37].

A royal decree is issued in April, 2010, to order the creation of the King Abdullah City for Atomic and Renewable Energy [75]. It aims to contribute achieving sustainable development in the Kingdom through exploiting the science, research and industry of atomic and renewable energy for peaceful purposes. King Saud University (KSU) established the Sustainable Energy Technology (SET) program to contribute in the field of sustainable energy focusing on solar, wind, hydrogen and nuclear energy. The university already initiated Master of Science programs in nuclear energy, and renewable energy [89]. The Clean Combustion Research Center at KAUST aimed to develop simple, cost-effective processes for supplying clean energy by combustion, partial oxidation, or other means relying on chemical energy conversion. The Center is also going to establish a graduate-level research program for the education and training of expert leaders on clean combustion technology [78].

4.5. Cogeneration

Cogeneration is the sequential production of two or more forms of energy from a common fuel source and it is used under different modes and technologies based on target application [40]. The main applications include the combined cycle power plants using gas and steam turbines, the desalination plants using either gas or steam turbines to supply electricity and heat to multi stage flash (MSF) desalination process, and the matching of gas turbines with heat recovery steam generators in the oil and gas industries [40]. The Saline Water Conversion Corporation (SWCC) of the Kingdom adopted simple hybrid multistage flash–reverse osmosis (MSF/RO) for its three large desalination plants at Jeddah, Al-Jubail and Yanbu [60]. In Saudi Arabia, 7 GW of total generation capacity representing 23%, is supplied through cogeneration [40]. According to Meed [99], the requirement of the Kingdom is about 1000 million of desalinated water galleons/day.

4.6. Master gas collection system

Saudi Aramco operates the world's largest single hydrocarbon network, the Master Gas Collection System (MGCS). Instead of flaring, the gas is collected, processed, and utilized through the network. This effort has remarkably (more than 99%) lowered CH_4 emissions from the Kingdom's oil and gas fields during the period 1980–2000.

4.7. Carbon capture and management initiatives

Saudi Aramco is participating in several research and technology programs to reduce GHG emissions by improving combustion efficiency, reducing carbon dioxide emissions and implementing carbon management. Saudi Aramco is the largest oil corporation in the world operating seven domestic refineries, 85 fields, 320 reservoirs, 48 rigs and more than 9000 miles of crude oil and natural gas pipelines [45]. Saudi Aramco arranged the first regional symposium on carbon management titled "Carbon management challenges and opportunities for the petroleum industry". It was held in Dhahran in May, 2006. Saudi Aramco plans to inject carbon dioxide into the world's biggest oilfield by 2012. The Kingdom plans to inject 40 million standard cubic feet per day (cfd) of CO_2 into the field. This effort will contribute in trapping emissions and enhancing oil recovery from the field. Saudi Aramco developed a carbon management (CM) technology roadmap which aims toward enhancing petroleum presence in global CM technological development, leveraging petroleum industry resources and know-how, and enhancing the value created from the carbon cycle.

Saudi Arabia is trying to clean up its act where pollution is concerned. The Saudi Government invested $300 million into research and development for projects directly linked to energy and the environment. Saudi Arabia was one of four countries signed up to the "Four Kingdoms" initiative. It aims to explore the environmental viability of carbon capture and storage (CCS) technology [26].

4.8. Solid waste management initiatives

Al-Turki [20] evaluated a variety of stability and maturity indices for 14 commercially produced composts in Saudi Arabia in order to acquire a comprehensive image of local compost quality and its compliance with local and international compost standards.

The strategic plans of the major cities are getting inspired by the concept of waste minimization. For example, the strategic plan of Jeddah which was initiated in 2005 emphasized on the programs concerning waste management in order to reduce landfill requirements. The 2nd International Recycling and Waste Management exhibition in Riyadh, Saudi Arabia which held from 1 to 4 November 2009, at the Riyadh, demonstrated the widespread recycling business present in the Kingdom.

4.9. Urban greenery development and green building initiatives

According to the estimation available in the literature, the commercial/residential buildings in Saudi Arabia consume 10–40% of the total electric energy generated [48]. Hasnain et al. [62] reported that the buildings' share could exceed 70% of the total electric energy use in the Kingdom. This kind of information inspired the Kingdom to take positive initiatives for greening urban areas and building energy efficient infrastructures. The National Spatial Strategy (NSS) of the Kingdom will provide principles and guidance on ways to support development and address the social and environmental consequences of development, including ways to integrate low-emissions approaches to urban planning.

In January 6, 2010, the deputy minister of municipal and rural affairs inaugurated development projects around Jeddah which included a 2.5-million-square-meter forestation program near the sewage lake in east Jeddah, and a garbage separation and recycling plant at the new landfill in Asla. In the same occasion, the mayor informed about one of many potential greenery projects that include a national park, a safari park and many other entertainment facilities. The project would cover an area of 100 million square meters. In July 22, 2010 the Jeddah municipality informed that it is currently planting 160,000 plants in Wadi Al-Asla [27]. In the second phase, the forested area would be expanded further to eight million square meters, planting 360,000 fragrant flowers and herbs. The Royal Commission for Jubail and Yanbu is currently implementing new projects worth SR1.4 billion in Yanbu, including a seafront project which is aimed at attracting more tourists to the city and providing them with all required facilities including greenery. In Yanbu, the Huzam Al-Akhdar project is spread over an area of nine kilometers along King Abdul Aziz Road and as many as 22,000 trees and 200,000 flower plants have been planted in the area. It has greenery

covering 70,000 square meters. In Yanbu, the newly opened Fairouz Gardens, believed to be the most beautiful garden in Yanbu covering an area of 72,300 square meters. The garden has a large map of the Kingdom covering 1200 square meters.

Energy efficient buildings limit greenhouse gas emissions and can improve indoor and outdoor air quality, and ultimately help improving social welfare and enhancing energy security. A conference was held in October, 2010 in Riyadh to declare the inception of the Saudi Green Building Forum (SGBF) which is a key milestone in the Kingdom's on-going efforts to raise awareness and promote sustainability. It will provide a crucial industry forum to debate best practice on design, construction and the built environment. The event focused on the role that the wider community has to play in achieving an environmentally sustainable future. Saudi Green Building Council (SGBC) attempts to encourage the concept of green building in the context of Saudi Arabia which is the outcome of energy efficient, resource efficient and environmentally responsible building. The Saudi Green Building Council was granted prospective GBC status.

4.10. Transportation related initiatives

Railroads typically release less GHG compared to other modes of transport. Recently, the Kingdom initiated the North-South Railway (NSR) project which is the world's largest railway construction and the longest route to adopt the European train control system (ETCS) to date. It is a 2400 km passenger and freight rail line originating from the capital city Riyadh to Al Haditha, near the border with Jordan. It is expected that the passenger service will start at the end of 2010 and the freight service will start in between 2011 and 2012. The Al Mashaaer Al Mugaddassah Metro Line project in Makkah involves the construction of a 20 km-long metro line. It connected the holy cities of Mecca, Arafat, Muzdalifa and Mina.

4.11. Awareness campaign

Nationwide, an energy saving program known as National Energy Efficiency Program (NEEP) was launched by the MOWE to use all means to conserve the energy in all sectors right from a single house to an industry. The main objective of the NEEP is to educate the masses know about the importance of energy conservation and ways and means to implement these. The first national "Solar Communication and Coordination Workshop" was hosted by the KAUST. Apricum, a strategic consultancy specialized in renewable energies initiated and conceptualized the conference. More than 150 representatives of the Saudi Arabian industry, government and research institutions that have a significant influence on the development of solar energy in the country, followed the invitation and met on May 16, 2010. The 5th Renewable Energy Workshop titled Solar Energy Technology: Present and future was held at KFUPM on April 24, 2010 for enhancing awareness about utilization of technologies based on renewable energies.

The Saudi government announced to support essentially the development of public awareness regarding the climate change [54]. In order to promote the fundamental benefits of solar energy to the general public, the ERI and the KACST participated in a number of energy related exhibitions. ERI conducted a survey on the availability of solar-energy educational programs at different educational levels around the world. According to Alawaji [8], public awareness has been developed in the Kingdom by giving extra emphasis on solar-energy education programs.

Green Jeddah is Saudi Arabia's first youth-led eco-friendly initiative. The students from all over Jeddah are involved in kicking off the green movement within the city of Jeddah. The core objective of Green Jeddah is to promote recycling and other green practices in the name of sustainable living within the region. The Presidency of Meteorology and Environment (PME) is currently working to prepare a national strategy for environmental awareness that will support the environmental legislation in the country. According to Alawaji [6], a number of energy-related exhibitions to demonstrate the importance of solar-emerging technologies have been implemented in the Kingdom. All these efforts are believed to address reduction of GHG emissions.

4.12. International treaty, and plan, policy, and program initiatives

Saudi Arabia agreed to the UNFCCC on 28 December, 1994. The Saudi government announced to support essentially the development of public awareness regarding the climate change [54]. The Kingdom has signed the Montreal Protocol for phasing-out Ozone Depleting Substances (ODS), and within the framework of a national strategy, industrial facilities/plants are gradually stopping the use of certain ozone depleting chemicals. United Nation Development Program (UNDP) and the Government of Saudi Arabia launched in June 2010 a new Urban Planning project that will help guide the shape and pace of urbanization. It is set to change the Kingdom's development landscape over the next decade. Key outcomes of the project include updates to the NSS and establishment of a new nation-wide Urban Observatory Network (UON) to support monitoring and evaluation of local governance and urban development indicators.

The Gulf Cooperation Council (GCC) will establish a Center of Excellence in Renewable Energy Research in Saudi Arabia and the remaining member countries. The center is to be set up under auspices of United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Islamic Educational, Scientific and Cultural Organization (ISESCO).

The Electricity and Cogeneration Regulatory Authority (ECRA) has taken initiatives to develop regulatory framework for the promotion of clean and renewable sources of energy to generate power in the Kingdom. The first draft was presented before policy makers, academicians, researchers, industrialists, and participants from various other government and non-government organizations by ECRA during a workshop held in June 2009 in Riyadh. These rules, regulations and policies are intended to promote the utilization of clean and RES in the Kingdom. Reid and Goldemberg [120] found out the carbon savings of around 3.9 MtC within 1990–1995 for the Kingdom using World Bank estimates of price elasticities of demand and inflation-adjusted internal fuel prices.

The Kingdom aims to develop renewable and nuclear energy resources to substitute significant amount of crude oil and natural gas it burns now for generating electricity. Khalid Al Sulaiman, vice president for renewable energy at King Abdullah City for Atomic and Renewable Energy said that energy other than fossil fuels may account for more than half of the Kingdom's supply by 2030 [61]. On March 28, 2011 in a conference in Abu Dhabi, UAE Al-Shehri, governor of the ECRA said that Saudi Arabia will invest more than $100 billion over the next ten years in order to expand generating capacity and the transmission grid and a third of that amount will be utilized for building power plants including renewable energy sources. The Kingdom made an agreement with France in February, 2011 for cooperation in developing nuclear energy along with the use of geothermal, wind and solar energy [61]. It plans to spend over $100 billion for 16 nuclear reactors for meeting domestic energy needs. Melaibari, coordinator of scientific collaboration at KA-CARE said, "After 10 years we will have the first two reactors. After that, every year we will establish two, until we have 16 of them by 2030" [127]. The Kingdom signed a bilateral agreement with South Korea for cooperation in research and development, including building nuclear power plants and research reactors, as well as training,

safety and waste management [134]. It also made similar kind of agreement with Argentina [52].

5. Present and potential future research initiatives

It is already found out that electricity generation, road transport, fuel combustion in desalination plants, and solid waste management are the typical key contributors for the Kingdom. Due to the huge infrastructure development projects in the Kingdom, the role of the cement industry is also expected to be significant in greenhouse gas reduction. Therefore, it is imperative to develop future research strategy focusing on the areas which have high potentials for greenhouse gas reduction. In the following paragraphs a few key research initiatives will be discussed. These initiatives can contribute in developing relevant research attempts in the Kingdom and shaping the future research strategies. Koschikowski and Heijman [88] investigated the use of renewable energy in desalination processes. At the Fraunhofer Institute of Solar Energy systems, a system is developed to produce fresh drinking water using independent solar power supply. They also discussed on a project at Delft University of Technology which used wind energy to produce a safe and reliable source of drinking water for small communities through desalination processes. Hybrid desalination systems combining both thermal and membrane desalination processes with power generation systems are characterized by flexibility in operation, less specific energy consumption, low construction cost, high plan availability and better power and water matching [60]. Hamed [60] investigated the approach for pretreatment of seawater makeup feed to multistage flash (MSF) and sea water reverse osmosis (SWRO) desalination process with the help of nanofiltration membranes. Gude et al. [59] investigated the factors such as plant size; feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource in order to suggest an appropriate shift in the dependence of desalination processes on to the renewable sources from non-renewable sources. Gude et al. [59] commented that solar and wind energy sources can be more promising in terms of economic and technological feasibility although the applicability depends strongly on the local availability of these resources and the quality of feed source to be desalinated. They also focused on the low-grade reject heat sources or process waste heat sources such as domestic air-conditioning systems, geothermal sources and low-grade solar collectors for desalination processes. Therefore, it can be an inspiring research initiative to evaluate the feasibility of renewable energy based desalination plants in the Kingdom as the desalination plants mainly consume heavy fuel oil, crude oil, and natural gas along with a small share of diesel oil.

As a leading oil producing country, Saudi Arabia may consider the alternative technologies which will permit the consumption of fossil fuels with reduced GHG emissions. Although the fossil fuel based power plants contribute heavily in GHG emissions, fossil fuels are available on a mid and long-term basis and their continued large-scale and widespread applications in power generation industry are essential to maintain current economic growth in the world [150]. In the same line of thought, IEA commented that no single technology can meet energy challenge by itself and different regions and countries will require different combinations of technologies to best serve their needs and best exploit their indigenous resources [70]. As power generation has a significant share of CO_2 emissions, this sector offers opportunities to significantly reduce greenhouse gas emissions. Unfortunately, the renewable energy sources such as wind and solar energy are still up to a factor of ten more expensive than conventional energy sources [35]. It inspired to install Zero Emission Power Plants (ZEPPs) in which natural gas is combusted to generate electricity and the CO_2 is separated and injected into oil or gas reservoirs. The conventional separation of CO_2 from gas-fired power plants leads to reduction of overall efficiencies. As an alternative, the solid oxide fuel cells are fed with natural gas and produce electricity, water and CO_2. The high efficiency of fuel cells and easiness of CO_2 separation contribute in increasing the overall efficiencies.

Solar energy resources are in the forefront of current research under the area of renewable energy resources. Different innovative contribution in improving the cost-effectiveness and technological development is paving the path for potential dependency on solar energy. For example, Space Solar Power System (SSPS) is PV power generation system which generates electric power during Earth's orbit and sends the power to the ground by a microwave beam [98,108]. The next five paragraphs illustrate different applications of solar energy and relevant reviews.

Zahed et al. [152] considered the proposition of converting solar energy into hydrogen using electrolysis of water as a necessary, viable and challenging approach. They also discussed the present and future utilization of hydrogen in the Kingdom. Adbel-Aal [1] proposed an approach for the decomposition of water to hydrogen using solar energy and established a set of criteria for selecting appropriate regions and locations for hydrogen production on a massive scale in some parts of the Arab World. Abdel-Aal and Hussein [2] investigated the electrolysis of alkaline water and brine, and saline water for the production of hydrogen by analyzing the effects of salinity, voltage, current density and quantity of electricity. Almogren and Veziroglu [17] proposed a model, using the variables including population, energy demand and production, hydrogen production, energy prices, gross national product, environmental damage and quality of life for the solar hydrogen energy system for Saudi Arabia considering the dynamic interaction between the population, energy, economic parameters and the resources. Zahed and Bashir [151] assessed the performance of Syltherm-800 (a proprietary heat transfer fluid) and Partherm-290 (a proprietary heat storage salt) using the data collected from a solar powered freeze desalination pilot plant with a capacity of 200 m^3. The mentioned heat transfer media may ensure their prolonged use in solar power-generation technology due to the thermal stability [151].

El-Sebaii et al. [50] developed transient models for a single slope–single basin solar still with and without phase change material (PCM) under the basic liner of the still and performed numerical calculations for typical summer and winter days for Jeddah, Saudi Arabia. They concluded that PCM is more effective for lower masses of basin water on winter compared to summer season. El-Sebaii et al. [51] simulated and investigated an active single basin solar still integrated with a sensible storage material (sand) for the climatic conditions of Jeddah. They found out that the daily productivity decrease with the increase in the mass of sand and the daily productivity and efficiency decrease with the increase in the thermal conductivity of the basin liner material. Sabbagh et al. [124] investigated the design and performance of water heaters and distillers using solar energy for household utilization purposes. They found out the feasibility of locally building a solar water heater with a daily hot water capacity of 50 L at average of 70 °C and a water distiller with a daily average yield of 5 L. According to Sayigh [130], solar water heating is cheaper than conventional methods.

The ERI, along with the Ministry of Agriculture and Water (MOAW), conducted various research studies to develop efficient systems for drying dates (fruits) using solar energy at the Al-Hassa and Qatif Agricultural experimental sites [8]. Solar-powered agricultural irrigation can be an attractive application of renewable energy depending on the technical and economical feasibility. Kelley et al. [80] proposed an approach to determine the technical and economic feasibility of PV powered irrigation systems. Said [126] investigated the economic competitiveness of PV-powered

irrigation compared to conventional diesel powered pumps in Saudi Arabia and presented a cost breakdown of a solar PV module of US$2.5/W at a peak load. Radhwan and Fath [113] evaluated the thermal performance of an agricultural greenhouse, constructed in Jeddah, Saudi Arabia with a built-in solar distillation and provided a set of measures to improve the productivity of the greenhouse solar distillation. Al-Helal and Alhamdan [12] investigated the performance of a greenhouse polyethylene cover exposed to the arid environment by measuring global solar radiation (GSR), photosynthetically active radiation (PAR), air temperature and relative humidity inside and outside of the model structures. Abdel-Ghany and Al-Helal [3] suggested using simulation models in predicting the greenhouse environment and proposed general relations for estimating the amounts of solar energy absorbed by the greenhouse components and lost to the surrounding environment.

Solar desalination can directly utilize solar energy to produce distillate in the solar collector or can combine conventional desalination techniques including multistage flash desalination (MSF), vapor compression (VC), reverse osmosis (RO), membrane distillation (MD) and electrodialysis (ED), with solar collector for generating heat [65]. Direct solar desalination compared to the indirect technologies has low productivity but competitive in small-scale production due to low cost and simplicity [112]. The investigation of coupling solar energy with desalination technologies revealed that solar thermal is most appropriate for thermal processes such as MSF [65] but PVs can supply energy for processes like VC and RO [97,105]. Khawaji et al., Charcosset, Al-Karaghouli et al., Mezher et al. [15,33,81,100] reviewed existing and potential combinations of desalination and renewable energy technologies emphasizing on solar and wind energy. The present and future studies on solar thermal desalination focus on enhancing solar energy collection, improving the technology of desalination techniques and better matching the solar [15]. The Kingdom produces 18% of the world's desalinated water [65]. The adoption of solar energy based desalination plants can reduce operational costs and subsequently, reduce consumer costs in the context of Saudi Arabia [22].

Kim and Infante Ferreira [84] reviewed various solar cooling technologies and evaluated with respect to performance and initial cost. Rehman and Halawani [117] reviewed Saudi initiatives related to the development and utilization of solar energy in the Kingdom. Parida et al. [106] provided an overview of major solar PV technologies including PV power generation, hybrid PV generation, various light absorbing materials, performance and reliability of PV system. Kazmerski [79] discussed different aspects of PV technologies, best research-cell efficiencies between 1975 and 2010, PV production values between 1975 and 2007, and technology investment pathways.

Al-Abbadi [4] analyzed the wind speed data between 1995 and 2002 of five sites and showed that two cities of Dhulum and Arar are possibly good candidates for off-grid wind turbines. He also concluded that the grid connected wind turbines are a viable option to partially power the coastal cities of Yanbo and Dhahran. Elhadidy and Shaahid [48] concluded through case studies that Dhahran is a viable candidate for installation of wind energy conversion systems (WECS) to meet the energy needs of buildings. But large stand-alone WECS will be required to manage the peak load in the months August–October and the offset in power can be taken care by integrating battery storage and diesel back-up systems. Standalone WECS may have considerable downtime during the year due to relatively high cut-in wind speeds at which WECS start producing usable energy. This problem can be solved by adopting hybrid-diesel systems. Another problem associated with WECS is that the fluctuations of wind energy generation mismatch with the time distribution of the load demand on a continuous basis. In order to reduce the time-distribution-mismatch between the load and the wind energy and to account for maintenance/outages of the systems, short-term battery storage can be incorporated with WECS [132,142].

In order to investigate the applicability of the combined utilization of renewable such as solar and wind energy, Elhadidy and Shaahid [47] analyzed hourly wind-speed and solar radiation measurements made at the solar radiation and meteorological monitoring station, Dhahran, Saudi Arabia, to study the impact of key parameters such as PV array area, number of wind machines, and battery storage capacity on the operation of hybrid (wind + solar + diesel) energy conversion systems, while satisfying a specific annual load of 41,500 kWh. Elhadidy [133] studied wind-speed data of Dhahran to investigate the role of hybrid (wind + diesel) energy conversion systems in meeting the load requirements of a typical commercial building. They found out that with thirty 10 kW WECS and 3 days of battery storage, the diesel back-up system has to provide 19% of the load demand but in the absence of battery storage, about 40% of the load needs to be provided by the diesel system.

Energy storage is considered as a means of reducing fossil fuels demand and the demand for new energy storage systems is increasing for applications including remote area power supply systems, stressed electricity supply systems, emergency back-up, and mobile applications [115]. Rahman et al. [115] provided a comprehensive overview of the various energy storage systems including mechanical, electrical and chemical systems to store electricity generated by renewable energy sources. They concluded that Saudi Arabia should focus on initiating R&D work to improve the technology as it is a key element for the growth of renewable energies.

Researchers are emphasizing on energy efficient buildings to reduce greenhouse gas emissions. The installation of outer skin surface technologies to buildings can reduce CO_2 emissions. These technologies include high light-reflective and high heat-emissive paint [87]. It also includes the low light-reflective and the low heat-emissive outer skin surface [71]. Kato et al. [77] commented that a micro co-generation system (CGS) using a polymer electrolyte fuel cell (PEFC) can improve energy efficiency in the residential sector because the micro CGS recycles waste heat from PEFC and supplies it as usable hot water in addition to its electricity supply. Kato et al. [77] analyzed the hot-water demand data in three residential households during several months in order to evaluate the actual efficiency of a micro CGS and they concluded that a micro CGS with a large hot-water tank and small backup boiler might be preferable for reducing primary energy consumption. Hasnain et al. [63] showed how Thermal Energy Storage (TES) offers a way of reducing the electricity demand in large commercial buildings in the Kingdom. They found out that efficiencies of the air cooled chillers are increased if they run overnight and the efficiency of gas turbine is also increased when a TES based pre-cooled air is used as an inlet to the turbine. They also focus on the favoring conditions and other aspects of cool storage applications in Saudi Arabia.

Approximately 5% of global anthropogenic CO_2 emits from the cement industry and it seems that the industry will receive explosive demand for its product over the next few decades [95]. The main cement-related emissions originate from fossil fuel combustion and the conversion process of limestone to calcium oxide. After quantitatively evaluating the current and potential future cement industry greenhouse gas emissions, Mahasenan et al. [95] determined the several challenges of this industry to reduce emissions. The challenges include heavy dependence on fossil fuels and limestone-based clinker, and the age and efficiency of its capital stock. The cement industry in Saudi Arabia relies on heavy fuel oil along with diesel oil and natural gas. A detailed study is required to investigate the current status of the efficiencies of the grinding and calcinations processes and develop appropriate

strategies to reduce GHG emissions. Replacing few clinkers with steel wastes, energy conservation and preheating in the cement kiln, the use of mill liners, grinding media and more complex grinding circuits can contribute in the reduction of energy consumption [73]. Li-Xia et al. [93] reported five low-carbon measures and implementation approach for Chinese cement industry such as: (1) increasing industrial concentration degree and developing new dry process cement; (2) processing waste in cement kilns and reducing the use of raw materials and fuels; (3) increasing the amount of admixture in cement; (4) producing cement from calcium oxide containing solid waste; (5) adopting energy-saving measures such as cogeneration and grinding technology. Rodriguez et al. [123] investigated a precalciner consists of a circulating fluidized-bed combustor (CFBC) operating at about 1050 °C connected with a fluidized-bed calciner to reduce the CO_2 emissions from an industrial cement plant by means of CO_2 capture and storage. Lam et al. [91] studied the feasibility of replacing clinker raw materials by municipal solid waste incineration ash residue for cement clinker production. These recent research initiatives should encourage the researchers to investigate the feasibility of similar kind of studies in the context of the Kingdom to improve the performance of the existing and future local cement industries in terms of carbon reduction.

ChevronTexaco Corporation is a leading global company which provides energy and chemical products and services that play an important role in the world's economies. In July, 2001 this company implemented the ChevronTexaco Energy and Greenhouse Gas Inventory System (CEGIS) which is capable to gather monthly energy and greenhouse gas emissions data from its worldwide exploration and production, refining and marketing, petrochemicals, transportation and coal mining activities [104]. The inventory included three direct greenhouse gases, namely CO_2, CH_4, and N_2O as other three Kyoto Protocol gases are not expected to be emitted in significant quantities during the operations of ChevroTexaco. The American Petroleum Institute (API) developed a Compendium of greenhouse gas emissions estimation methodologies for the oil and gas industry [24]. In addition to developing greenhouse gas emissions inventories, API is also investigating the appropriateness of the Compendium methodologies to assess emission reductions from specific case studies. One case study suggested that the emissions can be reduced from pneumatic devices that can be achieved through maintenance, retrofit or replacement of the devices, and replacement of natural gas with compressed air [122]. Combustion tuning approaches which include adjusting the burner air register settings to maintain uniform combustion air draft, adjusting the stack dampers to control air-to-fuel ration, cleaning burner tips or other blockages restricting air flow, and maintenance of combustion components, resulted an overall estimated emission reduction of 3% for one of the case studies [122]. The third case study promoted cogeneration which provides attractive energy efficiency and greenhouse gas reduction opportunities [122]. Saudi Aramco, being the world's largest oil corporation should investigate the appropriateness of conducting similar kinds of studies to develop GHG inventory for the company and monitoring systems which will ultimately benefit developing strategies to reduce GHGs.

According to Lutsey and Sperling [94], transport GHG emissions are increasing faster than those from any other sector. Therefore, it causes a substantial and increasing worldwide GHG emission challenge. GHG mitigation measures can be grouped into three main categories which include vehicle efficiency, environment friendly fuels, and travel demand reduction. Vehicle efficiency improvements can be obtained through incremental vehicle technologies, advanced technologies, and on-road operational practices. Lutsey and Sperling [94] mentioned that GHG emissions rates can be reduced by 20–30% by introducing more efficient combustion, more efficient transmissions, and overall vehicle advances, such as aerodynamics and light-weighting in new vehicles. Electricity driven propulsion technologies such as hybrid gasoline-electric vehicles, plug-in hybrids which use both electricity and petroleum fuels, battery electric vehicles, and hydrogen powered fuel cell vehicles, can contribute in reducing the life cycle GHG emissions by at least 80% [94,146]. Improvements to on-road vehicle efficiency including consumer education, vehicle maintenance practices, and off-cycle vehicle technologies can reduce GHG emissions up to 20% [94]. The transport fuel options such as compressed natural gas and liquefied petroleum gas can impact GHG emissions. Based on a survey Yang and Yu [148] concluded that buses are considered more energy efficient compared to cars and motorbikes. They also suggested that developing compressed natural gas (CNG) buses is a competitive option to promote environmental friendly urban passenger transportation for those countries where domestic natural gas resources are available (CNG and liquefied petroleum gas (LPG) are the least emission technologies so far). The reduction in travel demand can be obtained through transportation pricing and development policies and land use change. The applications of intelligent transportation systems can also contribute in reducing GHG emissions by streamlining traffic and reducing stop and go conditions. Chaaban et al. [32] suggested that switching to fuel with lower emission rates, improving the technical status of the fleet and system efficiency can be considered as the major mitigation options for transport. Kok et al. [85] reviewed thirty-three selected transport GHG mitigation studies and found out that methodological choices can lead to a difference by up to $400 per ton CO2-eq. Rahman and Al-Ahmadi [114] suggest emphasizing on Transportation Demand Management (TDM) strategies to ensure sustainable transportation in the context of Saudi Arabia. They concluded that the increasing trend of passenger cars in Saudi Arabia makes it more important to concentrate on TDM strategies as a tool for curbing vehicular pollution and congestion. Further research in the area of energy demand management through urban growth and transportation demand management can be very important areas of research in the context of Saudi Arabia to ensure reduced emissions of greenhouse gases. Al-Hathloul and Mughal [11] and Alshuwaikhat et al. [19] attempted to evaluate the growth management approach for Saudi Cities.

The solid waste management techniques based on local resources and supported by modern technological advancement can contribute in reducing the CH_4 emissions in the Kingdom. The local researchers such as Gondal and Siddiqui [58] applied Laser-Induced Breakdown Spectroscopy (LIBS) for the identification of various kinds of plastics for management and recycling of plastic waste and the capability of this technique is demonstrated by the analysis of the major constituents. The study demonstrated that LIBS can be considered as very useful tool for sorting out different kinds plastics on a fast scale for waste management. Ali [13] prepared compost using local Date Palm Leaves (DPL). He compared the performance of DPL and peatmoss on seed germination, rate of germination and growth of ornamental plants. The author concluded that the preparation of composts using local farm wastes resources such as DPL and *Phragmites australis* performs better than imported peatmoss. Yano et al. [149] found that a biogasification (high-temperature and dry-type methane fermentation) system with gas engine (GE) power generation emits less greenhouse gases than the direct combustion with steam power generation and direct combustion with composting.

Recycling based technologies play a significant role in the reduction of greenhouse gas emissions. It can include both recycling of wastes and recovering energy from wastes. In some cases, material recycling is not economically and technically viable option. In those cases, recovering energy from wasters such as thermal recycling can be promoted [86]. The power generation from Refuse

Derived Fuel (RDF) as an example of thermal recycling is investigated from the viewpoint of energy saving and reduction of environmental impact materials [102]. Komatsu et al. [86] investigated the applicability of RDF power generation with respect to energy saving and reduction of greenhouse gas (CO_2) emissions and they found out that it would be viable if it were used to produce significant electrical output by large-area waste treatment.

The industrial chemical synthesis and technological applications can be considered as the potential artificial sinks for CO_2. The present industrial use of CO_2, mainly in urea [121] and carbonate production, is equivalent to approximately 110 million tones CO_2/year. It is typically used in the industry as feedstock for the synthesis of chemicals, technological fluid, and source of carbon. Aresta and Dibenedetto [28] identified the potential of CO_2 in the production of polymers, methanol and carboxylates. Takagawa et al. [154] developed efficient catalysts for ethanol formation, while Kieffer et al. [83] produced higher alcohols using CO_2. Aresta et al. [29] reported an approach to artificially convert CO_2 into methane by methanogens, a class of bacteria known to operate under anaerobic conditions. Aresta and Dibenedetto [28] documented an innovative technology to use CO_2 as mild oxidant under controlled conditions. This process operates at much lower temperature than the currently used thermal processes. As a result of hydrocarbon oxidation and valorization this approach will be environment friendly in terms of energy savings and greenhouse gas emissions. Kuramochi et al. [90] reports a techno-economic assessment and comparison of CO_2 capture technologies for key industrial sectors including iron and steel, cement, petroleum refineries and petrochemicals. Although a large number of technologies are under development, it is too early to identify the future dominant technologies. Kuramochi et al. [90] concluded that a good integration of industrial plants and power plants is essential for cost-effective CO_2 capture due to the significant increase of the industrial onsite electricity production. The National Energy Technology Laboratory (NETL) of the United States Department of Energy (DOE) is pursuing advanced technologies in enhanced hydrocarbon recovery, chemicals production, mineralization processes, and plastics and polymer production [38]. De Visscher et al. [42] investigated the sinks of CH_4 through anthropogenic actions. A clear example of artificial sinks is the landfill cover soils and another example is the rice fields. Saudi Arabia already took steps toward CO_2 capture and storage but the national strategy concerning this issue is yet to be developed.

A few countries including the USA and Brazil have started to produce biodiesel and bioethanol using food chain sources but there is an alternative type of biofuels, originated from non-food feedstocks such as agricultural wastes, municipal wastes, microalgae and other microbial sources which are more attractive and more acceptable due their utilization of nonfood biomass as raw materials [107]. The use of microorganisms and their metabolic products is considered as one of the most significant fields of biotechnology activities. Mata et al. [96] reviewed the present status of microalgae use for biodiesel production and compared it with other available biodiesel feedstocks. They also presented other potential applications and products from microalgae for biological sequestration of CO_2, wastewater treatment, in human health, as food additive, and for aquaculture. The key factor for successful commercialization of microalgae-based fuels is the economic viability of the microalgae production process in terms of minimizing the operational and maintenance cost along with maximization of oil-rich microalgae production [136]. These studies may inspire the Saudi researchers to come forward and investigate different uses of the microalgae including biodiesel production, biological sequestration of CO_2 and wastewater treatment.

6. Conclusion

One of the strategic principals for the early five-year national development plans of the Kingdom provides environmental conservation, protection, and enhancement as well as prevention of pollution. These kinds of strategic principal inspired many important agencies of the Kingdom concerned or related to environment to come forward and take sincere initiatives to reduce GHG emissions. The ongoing research and development activities of the local universities and research organizations provided the initial justifications for the RES such as solar and wind energy conversion, and hybrid systems. The investment of the private sector in RES is paving the path of increased use of RES. The role of Saudi Aramco in carbon capturing and management along with other efforts to reduce GHG emissions indicates the excellence in environment related research. The agreement of the Saudi Government to comply with many international environment conservation treaties shows its commitments to the regional and global environment. Moreover, the volunteering initiatives of non-profitable organizations are increasing awareness about RES, RUE, and other environmental efforts among the public.

The Kingdom may consider country and region specific circumstances in developing policies and measures to reduce greenhouse gas emissions. The national emission strategy should be comprehensive, coherent, and consistent in order to develop short and long term plans for achieving GHG emission targets in an equitable and cost-effective manner without hampering other government commitments. The national interests and circumstances including geo-physical factors, demographic characteristics, institutional arrangements, and economic, social, cultural and religious issues should play a role in shaping the national strategies. Finally, the increasing integrated efforts should be made among the public and private sector, and the people to realize the need of sincere commitment and actions to reduce GHG emissions aiming to provide a sustainable environment for the present and future generations.

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